EARTH

EVOLUTION OF A HABITABLE WORLD

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1 AN INTRODUCTORY TOUR OF EARTH'S COSMIC NEIGHBORHOOD

1.1 ANCIENT ATTEMPTS TO DETERMINE THE SCALE OF THE COSMOS

The science of astronomy developed in many different cultures and from many different motivations. Because even in cities of the preindustrial world, the stars could be seen readily at night, the pageant of the sky was an inspiration for, and embodiment of, the myths and legends of almost all cultures. Some people tracked the fixed stars and moving planets with great precision, some for agricultural purposes (the ancient Egyptians needed to prepare for the annual flooding of the Nile River valley) and more universally to attempt to predict the future. The regularity of the motions of the heavens was powerfully suggestive of the notion that history itself was cyclical, and hence predictable. The idea of human history linked to celestial events remains with us today as the practice of astrology. In spite of a lack of careful experimental tests, or demonstrated physical mechanisms, this powerfully attractive belief system is pursued widely with varying amounts of seriousness, extending in the early 1980s to the level of the presidency of the United States.

Although ancient understanding of the nature of the cosmos varied widely and was usually a reflection of particular mythologies of a given culture, the classical Greeks distinguished themselves by their (often successful) attempts to use experiment and deduction to learn about the universe. Some Greek philosophers understood the spherical nature of Earth and something of the scale of nearby space. Aristotle, in the fourth century B.C., correctly interpreted lunar eclipses as being due to the shadow of Earth projected on the surface of the Moon. By noting that the shadow was rounded, he deduced that Earth must be spherical; in fact, another acceptable shape based on that one observation is a disk (figure 1.1). Others, such as Plato, had much earlier endorsed a spherical shape on aesthetic grounds.

Eratosthenes, who lived in the third century B.C., made a remarkably accurate determination of the size of our planet without having to travel too far. He used the observation that at high noon on summer solstice (June 21 in our calendar, when the Sun reaches its northernmost point in the sky of Earth), the Sun was directly overhead at a site in Syene (now Aswan), Egypt, because no shadow could be seen in the vertical well shaft. Eratosthenes lived in Alexandria, due north of Syene, and there he could observe that the Sun cast a shadow at noon on that same date of June 21 (figure 1.1).

What did this mean? If Earth were a sphere, then different people standing at different locations on Earth at the same time would see the Sun in different parts of the sky. By measuring as an angular distance in the sky, the change in the position of the Sun from one place to another and knowing the distance between the two stations, one could then by a simple calculation work out the circumference of the whole globe. In his home city, Eratosthenes carefully measured the size of a shadow cast by an obelisk of known height, at the same time on the same day that no noontime shadow occurred at Syene. The angular position of the Sun, from the size of the shadow at Alexandria, gave an angle of 7.2 degrees between the position of the Sun at the two stations, or one-fiftieth of the entire angular extent of the sky (360 degrees). Therefore, Earth's circumference, he knew, must be 50 times the distance between Syene and Alexandria.

The distance was, however, known only approximately from the number of days it took a camel to travel between the two towns and the distance a typical camel walks in a typical day. Furthermore, to compare the result with the value we know today, the units of measurement used

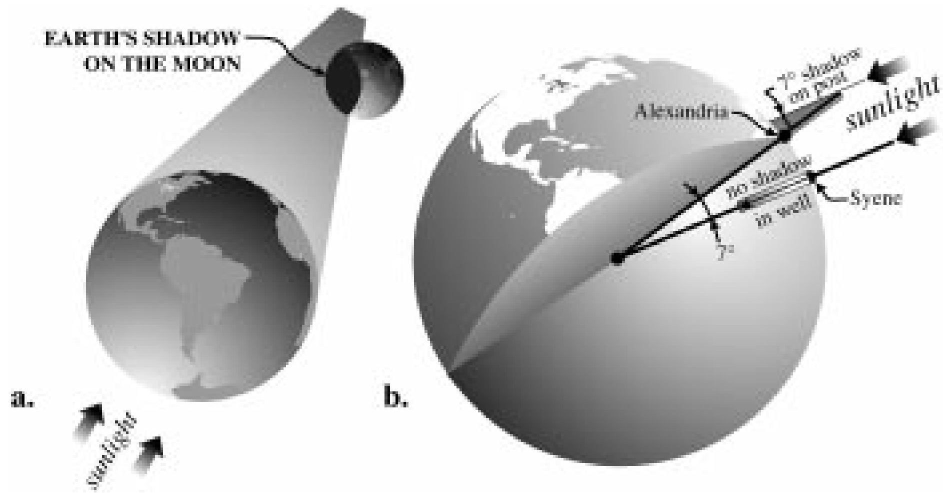

Figure 1.1. Two ancient Greek observations of the cosmos: (a) Aristotle's determination of Earth's sphericity via a lunar eclipse; (b) Eratosthenes' measurement of the size of Earth. Adapted from Snow (1991).

by the Greeks must be converted to modern ones, which is also an uncertain exercise. In modern units, the intercity distance is 570 miles, or 918 kilometers (km), and hence Eratosthenes' experiment yields an Earth circumference of 46,000 km, just 12% too large. This represents an extraordinary achievement, 2,300 years before human beings could view the round globe of Earth from space.

Not everything about the cosmos that the Greek philosophers deduced or inferred came out right. The most celebrated mistake was that of Ptolemy, who lived 400 years after Eratosthenes and is associated most closely with the cosmological system in which the Sun and the planets (in fact, the whole cosmos) were thought to orbit Earth. However, this was just the penultimate round in a long debate on the topic: Aristarchus of Samos, a generation before Eratosthenes, put the Sun at the center with Earth and the other planets orbiting it. This correct model of the solar system was discredited at the time because the Greeks could not see the stars shift in position as Earth moved from one point in its orbit to the opposite side. In fact, the stars do appear to shift position, as we describe later, but they are so far away that the shift cannot be detected with the unaided eye. This the Greeks did not know, and the failed experiment led them down the wrong path of an Earth-centered cosmos that would not finally be discarded until the times of Copernicus and Galileo, over 1,500 years later.

We should not fault the Greeks for their wrong interpretations, but should admire their startling successes, which were based on observations unaided by the technologies available at present, coupled with the disciplined logic of inductive and deductive reasoning which was the foundation of the scientific method. Few of us today could repeat the insights of these extraordinary philosophers. In point of fact, we in the industrialized world still have a mindset in essence of an Earth-centered universe: We think little of the sky, now obscured by the lights of cities and hence unfamiliar to us, unless it is to wonder when the Sun will set today, or what the local newspaper horoscope claims our immediate future will hold.

1.2 BRIEF INTRODUCTION TO THE SOLAR SYSTEM

The solar system consists of 9 planets, some 60 natural satellites (or *moons*), and innumerable small bodies, all orbiting the Sun. Robotic spacecraft have traversed the distance to the farthest planet in the solar system, some 6 billion km. The distance to the nearest star, Proxima Centauri, is 6,000 times greater; hence, we have no hope of seeing spacecraft reach such targets in the foreseeable future. In view of this, the solar system is our cosmic neighborhood, accessible for study by spacecraft and constituting the setting within which Earth has evolved through time.

Here the solar system is summarized in tutorial form to provide a context for what follows. The information presented is the result of at least three millennia of observations and insights, capped by three decades of intense scientific study from the ground and space. Some of this effort is described in the book, but to present a complete history of the exploration of the solar system would require a separate volume.

Figure 1.2 is a map of the solar system. The nine planets fall roughly into three classes according to their size

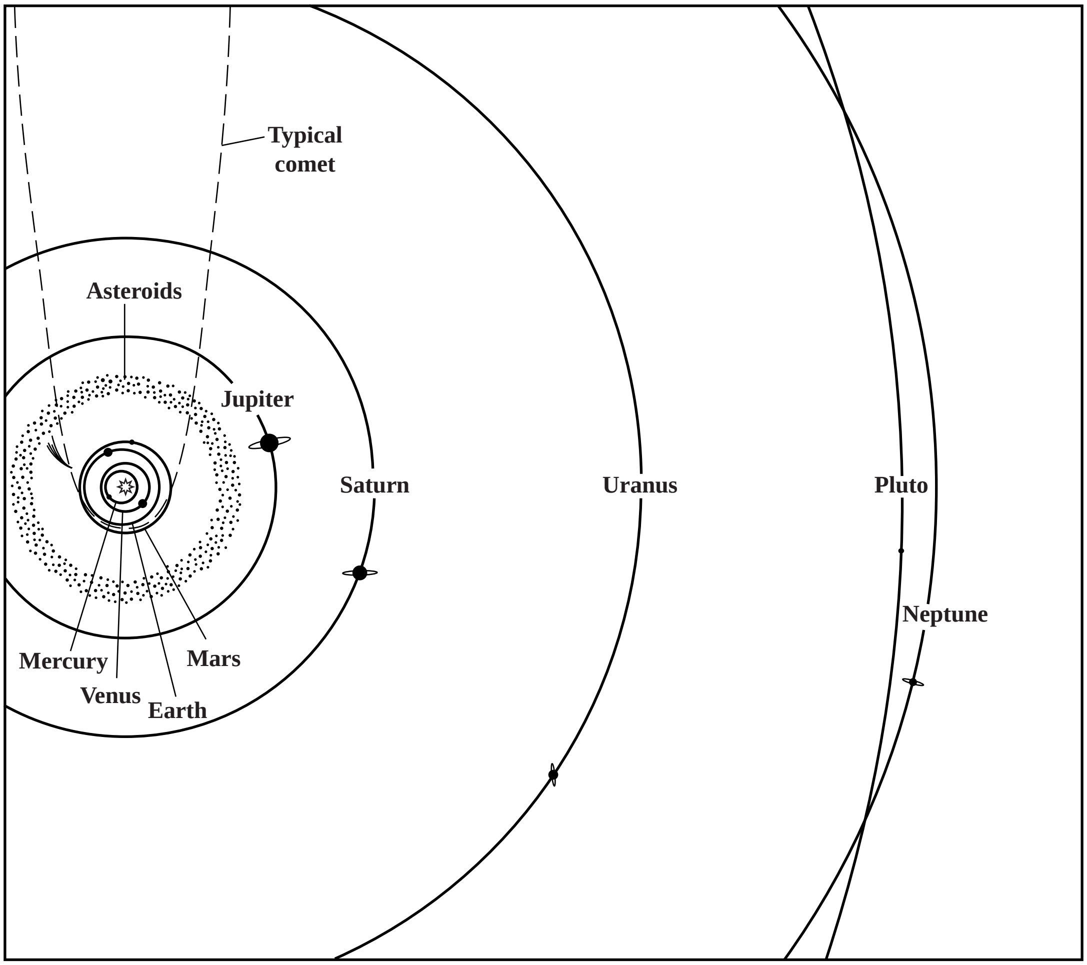

Figure 1.2. Schematic map of our solar system, showing the correct relative sizes of orbits but not of the bodies themselves. Note the small scale of the orbits of terrestrial planet compared to the vast realm of the outer planets. The Kuiper Belt objects just beyond Neptune's orbit and the Oort cloud of comets are described and depicted in chapter 10. Reproduced courtesy of Nancy and Larry Lebofsky, from *Our Solar System*, by permission of Arizona Board of Regents.

and composition. The four *terrestrial* planets – Mercury, Venus, Earth, and Mars – range in diameter from 4,800 km (Mercury) to 12,700 km (Earth). They occupy a small, inner region of the solar system, and are composed of a mixture of rocky and metallic materials.

The four *giant* or *Jovian* planets – Jupiter, Saturn, Uranus, and Neptune – are substantially bigger than Earth, ranging in diameter from 49,000 km (Neptune) to 142,000 km (Jupiter). They are much farther from the Sun than are the inner planets: Jupiter's distance from the Sun is 5 times that of Earth's and hence is abbreviated as 5 *astronomical units* (AU); Neptune is 30 AU from the Sun. In terms of common units of distance, Earth lies 150 million km from the Sun, and thus Neptune is more than 4 billion km from the solar system's center.

The giant planets are composed of a mixture of rocky and icy material and varying amounts of gases; Jupiter and Saturn are mostly hydrogen and helium gas whereas Uranus and Neptune are predominantly icy and rocky material with lesser amounts of hydrogen and helium gas. (Rocky and icy material is used here to mean atoms of silicon, magnesium, iron, oxygen, carbon, nitrogen, sulfur, and others that tend to form rocky and icy materials under conditions of normal pressure. Because of the intense pressures deep within these giant planets, much of the icy and rocky material is in atomic form, rather than the molecular form with which we are familiar.)

Beyond Neptune is the "oddball" planet Pluto, about 2,400 km in diameter (smaller than Earth's Moon), which may be the largest of a class of debris left over from the formation of the solar system. In size and density (amount of mass per volume in the object), Pluto is remarkably similar to Triton, the largest moon of Neptune.

Seven of the planets have at least one moon, with almost 60 such objects known to be orbiting the planets. Some are small, irregular fragments kilometers across; others – two moons of Jupiter, one of Saturn – are larger than the planet Mercury. The giant planets have multiple satellite systems, some in very regular, circular orbits, which can be considered as miniature solar systems. Saturn's largest moon, Titan, possesses an atmosphere thicker than ours on Earth; several other moons have tenuous atmospheres, including our own Moon which exhibits an extremely rarefied atmosphere of sodium and potassium. All of the planets have atmospheres, though that of Mercury is like our Moon's in being very tenuous.

The four giant planets have ring systems composed of debris from house-sized to dust, which orbits in the equatorial plane of the planet. Saturn's famous ring system is considerably more massive than those of the other major planets. None of the terrestrial planets possesses an organized ring system.

The solar system exhibits several regularities in its structure, which are important in understanding its origin, as we discuss later. All planets orbit the sun in nearly circular orbits, close to the plane of the Sun's equator, with the exception of Pluto, the orbit of which is both *inclined* (tilted relative to the sun's equator) and *eccentric* (significantly noncircular). All orbits are in the same direction; by convention, they are counterclockwise around the Sun when viewed from above the Sun's *northern hemisphere*. With two exceptions, Venus and Uranus, all planetary spins are in the same, counterclockwise, direction. However, the planetary rotational axes are all tilted relative to their orbital planes by varying degrees.

There is a strong correlation between the properties of the planets and their location in the solar system. The four terrestrial planets, which contain proportionately little water and gases, are closest to the Sun and not very massive compared to the giant planets. From Jupiter outward, solid objects (moons and Pluto) contain significant amounts of water ice and more volatile species. (Here, volatile refers to the tendency for a material to transform from a condensed state to a vapor.) The four giant planets seem to be of two classes, with the more gaseous planets, Jupiter and Saturn, closer to the Sun.

Viewed from a neighboring star, the most notable characteristic of the solar system would not be the planets, but the debris of small solid bodies outside Pluto's orbit. Only in recent years has the structure of these debris regions become evident. The orbit of Pluto extends from just inside Neptune's (29 AU) outward to nearly 50 AU. Within this region over 60 objects with diameters of a hundred kilometers or so have been detected orbiting the Sun. They are thought to be representative of a class of material, referred to as *Kuiper belt objects*, that are the leftover debris from the formation of the outer planets. The inner edge of this thick belt of material is defined by the giant planets, whose strong gravitational fields have swept the region from 5 to 30 AU clear of debris.

Well beyond the Kuiper objects lies more icy and rocky material in distant orbits ranging out to perhaps 100,000 AU from the Sun. The presence of such material is inferred from the existence of comets, rock-ice bodies perhaps 1–10 kilometers in diameter that come into the inner solar system on highly noncircular, that is, elliptical, orbits. Careful plotting of the paths of comets indicates that most of the orbits originate in an ill-defined shell of material termed the *Oort cloud*. The comets are the small fraction of Oort cloud objects that fall inward to the Sun after having been perturbed by close-passing stars. The total number of comet-sized Oort cloud objects may approach one trillion.

Remote observation of comets as they pass through the inner solar system suggests that they are accumulations of dust, organic material, water ice, and frozen gases. The Oort cloud material is thought to have been ejected from the 5- to 30-AU region by the giant planets after their formation and, in addition to comet-sized bodies, both larger and smaller objects may reside in this cloud.

Between the orbits of Mars and Jupiter lie belts of rocky objects known as asteroids. The largest asteroids are several hundred kilometers across; in number and total mass they are minuscule compared to the Oort cloud and the Kuiper belt. They are thought to be debris that never formed into a planet because of the proximity of Jupiter, whose gravitational field prevented efficient growth of a large body from smaller ones. Another collection of asteroids crosses the orbit of Earth–the so-called *near-Earth asteroids*, some of which may be old comets that have lost their mantles of ice after many passes by the Sun. Finally, lanes and regions of dust released from comets or asteroids lace the solar system; the precise distribution of this material, some of which can be seen faintly after sunset as the *zodiacal light*, remains somewhat uncertain.

The history of collisions between the numerous bits of small debris and the planets is recorded by the ubiquitous existence of craters throughout the solar system. Even Earth shows the scars, Meteor Crater in Arizona being a famous recent example. As we shall see, impacts may have played key roles in the origin and evolution of life on this planet Earth.

1.3 QUESTIONS

a. Consider how you have responded to a controversial scientific or technological issue. Did you try to weigh rationally the pros and cons, or did you respond on the basis of your instincts or emotions?

b. Imagine that the knowledge leading to atomic energy had never been achieved. What are some of the things that might have been different about the period from World War II to today? Can you say whether the world would have been better or worse off?

1.4 READINGS

1.4.1 General Reading

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1.4.2 References

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